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Wear on the deciduous molars in a Mediaeval English human population: a study using crown height

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A R T I C L E I N F O

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A B S T R A C T

This work comprises a study of mandibular deciduous molar wear in an archaeological population using measurement of crown height. The aims are twofold. Firstly, to investigate the nature of the relationship between wear on the deciduous molars and dental age. Secondly, to evaluate, using crown height, two existing methods of recording deciduous molar wear: the measurement of the percent of the occlusal surface made up of exposed dentine described by Clement and Freyne (2012), and the ordinal wear stage method of Dawson and Robson Brown (2013). The study material is immature skeletal remains ($N = 76$, dental age range 15 months–11.5 yrs) from a British Mediaeval site. Results show that crown height bears an approximately linear relationship with dental age for both first and second deciduous molars, and regression residuals are homoscedastic suggesting little inter-individual variation in wear rates. The second molar wears at a faster rate and its crown height bears a closer relationship with dental age. In the second molar, percent dentine exposure bears a non-linear relationship with dental age and with crown height, and for both molars the regression residuals of percent dentine exposed upon dental age are heteroscedastic. The ordinal wear stages of Dawson and Robson Brown (2013) are strongly correlated with dental age but different wear stages may correspond to dissimilar increments of crown height. Molar crown height is a sensitive and direct measure of occlusal wear, and its homoscedastic, linear relationship with dental age facilitates controlling for the effects of age when dental wear is used to study childhood diet in archaeological populations.

1. Introduction

Dental wear is the gradual wearing away of tooth substance that occurs as a result of natural mastication. At a population level, the physical properties of consumed foods are the prime determinant of the rate of wear; diets that are more abrasive and/or require more vigorous mastication lead to higher wear rates (Sengupta et al., 1999; Antón et al., 2011). Consequently, modern Western populations, reliant on soft, refined, factory-produced foods, show minor dental wear. By contrast, in antiquity, high rates of tooth wear were universal, reflecting coarser, tougher diets. The ubiquity of dental wear in ancient skeletal remains has meant that it has long been a focus of study in physical anthropology (e.g. Broca, 1879; Keith, 1916; Ruffer, 1920; Leigh, 1925). Because of the age-progressive nature of dental wear, much work has focused on its use for estimating adult age (Miles, 1978; Brothwell, 1989; Walker et al., 1991; Mays, 2010: 71–76), but it has also been used to study ancient diets and food preparation techniques (Powell, 1985; Larsen, 1997: 247–258; Rose and Ungar, 2001). Most publications concentrate on wear in the permanent dentition, but a few studies have begun to explore the potential of wear on deciduous teeth to shed light on childhood diet in past populations.

Skinner (1997) compared middle and upper Palaeolithic juveniles from western Europe ($N = 82$ individuals). Dental wear rates in the two periods were similar, but wear seemed to begin at younger ages in the upper Palaeolithic, suggesting earlier introduction of solid foods. Examining 37 subadult burials from 1st–3rd century AD Italy, Prowse et al. (2008) found that deciduous molar wear began in the second year of life, showing that weaning foods were significantly abrasive. Clement and Freyne (2012) studied wear in the deciduous dentition of 37 individuals dating to 12,000BC–16th century AD from Sudan. Exposed dentine on the anterior teeth was found in individuals as young as 18 months of age, suggesting early mastication of abrasive matter. Dawson and

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Robson Brown (2013) studied deciduous dentitions of 142 subadults from Mediaeval (11th–16th century) England, and found no difference in wear with respect to social status.

Although all the above studies found a pattern of increasing wear with age, some fundamental questions, such as the mathematical form of the relationship between wear and age, and whether the first and second deciduous molars wear at similar rates, remain to be addressed. These are significant matters, as a deeper understanding of deciduous molar wear potentially allows more detailed insights into early childhood diet in ancient populations. The studies cited above recorded molar wear using ordinal wear scales – i.e. wear stages – based on the visual appearance of enamel polishing and, in more worn teeth, dentine exposure (Skinner, 1997; Prowse et al., 2008; Dawson and Robson Brown, 2013), or else measured the proportion of the occlusal surface made up of exposed dentine (Clement and Freyne, 2012). Such techniques, whilst useful for many purposes, are not suited to addressing the above questions. Different wear stages on a given tooth may potentially correspond to unequal increments of crown substance removed and may differ on different molar teeth. The relationship between the proportion of the occlusal surface made up of exposed dentine and the amount of crown substance removed is likely to be rather inconsistent because a given decrement in crown height may correspond to different increments in exposed dentine depending upon how worn the tooth is. The principal effect of occlusal wear is loss of crown height. Crown height is thus potentially a more direct and precise measure of dental wear.

Studies in adult skeletal remains of documented age at death (Walker et al., 1991; Mays, 2002; Benazzi et al., 2008), in juvenile skeletal remains where age can be determined from dental development (Mays et al., 1995), and in living children (Molnar et al., 1983) suggest an approximately linear relationship between crown height in the permanent molars and age in populations that show appreciable dental wear. Permanent molars within the same jaw also appear to wear at fairly similar rates over the adult life course (Mays, 2002; Benazzi et al., 2008). Deciduous molars differ from the permanent molars in terms of morphology, size (Brown, 1984), structure (Bayle et al., 2009; Mahoney, 2010, 2013) and mechanical properties (Correr et al., 2007; Low et al., 2008; de Menezes Oliveira et al., 2010). These considerations, *inter alia*, mean that extrapolating the above findings for the permanent molars to the deciduous molars is problematic. Some studies have investigated loss of dental hard tissue at the occlusal surface of deciduous teeth in modern industrialised populations (Kreulen et al., 2010). However, these have used ordinal scales rather than crown heights to measure wear. Furthermore, modern Western diets are minimally abrasive and do not require vigorous mastication; the mechanism of loss of occlusal hard tissue in modern children appears fundamentally different from that likely in antiquity and appears to be mediated by dissolution by acidic components in the diet, particularly factory produced soft drinks (Milward et al., 1994; Johansson et al., 2001; Murakami et al., 2011; Gatou and Mamai-Houmata, 2012). Observations made on modern children are therefore of little relevance to palaeopopulations.

Measures of crown height are used in the current work to investigate the nature of the relationship between wear on the first and second deciduous molars and dental age, and to investigate the question of whether wear rates are similar on the first and second molars. In addition, two recently developed methodologies for studying deciduous tooth wear - the ordinal wear-scale of Dawson and Robson Brown (2013), and the method involving quantification of exposed dentine on the occlusal surfaces described by Clement and Freyne (2012) – were evaluated by investigating their relationships with crown height and with dental age.

2. Materials and methods

The current study uses juvenile skeletal remains from the churchyard at the deserted village of Wharram Percy (Mays et al., 2007). The remains date from the 10th–19th century AD, but the bulk are 11th–14th century. They are an inland, low status, rural population. A number of attributes make the Wharram Percy collection suitable for the current investigation. Study of the permanent teeth provides no evidence for secular change in the rate of dental wear during the period of use of the burial ground (Mays et al., 2007). The rate of wear on the permanent teeth, estimated using the methodology of Miles (1963), resembles that described by Brothwell (1981) as typical for Mediaeval and earlier British populations, increasing the likelihood that observations made on this population will have wider relevance. The individuals interred in the churchyard comprise inhabitants of the village of Wharram Percy and villages and farmsteads elsewhere in the parish. They therefore form a geographically and socially coherent population.

At Wharram Percy, the agrarian economy provided the dietary staples. Documentary sources, and archaeological evidence from the settlement part of the site, indicate the cultivation of cereals including wheat, barley and oats, as well as the raising of livestock for meat and dairy products (Dyer et al., 2012a,b). Stable isotope analyses of the Wharram Percy skeletons confirm a predominantly terrestrial diet (Richards et al., 2002). The isotopic results from the infants and children indicate that breastfeeding normally ceased at about 18 months of age (Richards et al., 2002), a pattern consistent with Mediaeval documentary sources (Fildes, 1986). $\delta^{15}N$ also indicates a childhood diet that was isotopically slightly lighter than adult diet (Richards et al., 2002). Whether this meant a greater reliance on plant foods or some other dietary difference was unclear, and Mediaeval written sources are largely silent concerning children's diets.

A dental age was assigned to each individual using the schedule of Massler et al. (1941), complied from studies on mid 20th century children from the Chicago area. Due to the imperfect relationship between dental and chronological age, errors accrue when estimating the latter from the former. The current work does not attempt to do this, but is confined to investigating the relationship of molar wear to dental age. Dental development was assessed on the gross specimens, augmented with radiography as necessary for intact jaw bones. All radiographs were taken by one of us (SM) using industrial grade film at exposures of 60kv for 10s. All were taken in lateral view. No attempt was made to determine sex. Wear was studied in the mandibular first and second deciduous molars (hereafter dm1 and dm2). Mandibular teeth were selected, following Dawson and Robson Brown (2013), because mandibular elements more often survive in the burial environment. To be included in the current work, a mandible needed to have both a dm1 erupted and a dm2 present for recording (either unerupted or erupted). At Wharram Percy, eruption of dm1 occurred at a dental age of about 1–1.5 years and dm2 at about 1.5–2 years. Both deciduous molars were shed at dental ages of about 11–12 years. The study group ($N = 76$ burials) comprises juveniles with dental ages of approximately 1.5–11.5 years.

In a mandibular molar tooth, the buccal cusps are the supporting cusps; they bear the brunt of crushing and grinding and wear more rapidly (Mills, 1978; Penido et al., 1979; Osborne, 1982). Crown height measurements were taken on the buccal sides of dm1 and dm2. The small size of the deciduous molars and lack of consistent landmarks on the occlusal surface to measure from led us to suspect that it would be difficult to obtain satisfactory crown height measurements using callipers. Instead, all measurements were made from digital photographs taken in standard orientation. The deciduous molars were photographed in their sockets in lateral

(buccal) view. One photograph was taken on each side of the jaw. It was centred on the interproximal contact point between dm1 and dm2 and was large enough to include both molar crowns in their entirety. If jaws were damaged so that teeth could not be placed in their sockets, the loose teeth were positioned together in their correct orientations in a sandbath. Using ImageJ software (Ferreira and Rasband, 2012), on the images of each molar, landmarks were placed on the mesial and distal extremities of the cemento-enamel junction (CEJ) on the buccal side, and a straight line drawn between them. The length of this line was measured in pixels as the mesio-distal length (MDL). On the dm2, two lines were drawn at right angles to this line from its mesial and distal ends to the top of the buccal side of the crown. The lengths of these two lines, denoted mesial crown height (MCH) and distal crown height (DCH) respectively, were measured in pixels. On the dm1, the DCH was measured in a similar way to that on the dm2, but because of its different morphology, a vertical line drawn from the mesial extremity of the CEJ on the buccal side in the dm1 would not, except in cases of advanced wear, normally intersect the occlusal surface of the crown. Therefore, MCH was measured in a slightly different way. A line was drawn at right angles from the line defining MDL to the top of the mesio-buccal cusp; this perpendicular line was moved along the MDL line (but never beyond the mesial extremity of the CEJ) to locate a maximum measurement. The length of this line, in pixels, was the MCH on the dm1. These measurements are illustrated in Fig. 1.

For each molar, the crown height index (CI) was calculated as:

$$\mathrm{CI} = 100 \times \frac{(\mathrm{MCH} + \mathrm{DCH})/2}{\mathrm{MDL}}$$

This is a measure of crown height on the buccal side of the molar, normalised for mesio-distal tooth length at the CEJ.

The percentage of the occlusal surface that comprised exposed dentine was measured from digital photographs. Vertical photographs were taken, one of each side of the mandible, with the image centred on the interproximal contact between the two deciduous molars and large enough to include both crowns in their entirety. Teeth were photographed in their sockets, but when this was not possible, due to the sockets being missing or damaged, the loose teeth were positioned upright and adjacent to one another in their anatomical positions in a sand bath. The area of the occlusal surface, and the total area of any exposed dentine within it, were measured from the images using ImageJ, as described by Clement and Freyne (2012). The total area of exposed dentine on a molar was expressed as a percentage of the total area of its occlusal surface to give percent dentine (hereafter PD). In the Wharram Percy specimens, the dentine was generally yellowish in colour. In many cases, islands of exposed dentine were surrounded by enamel which was sufficiently thin for the underlying dentine to show through as a yellowish colouration. On the images it was sometimes difficult to distinguish instances where yellowish colouration indicated exposed dentine from when it indicated dentine that was covered by a thin layer of enamel. In order to resolve such cases, the specimen itself was examined. Lastly, occlusal wear on dm1 and dm2 was scored, from careful visual examination of the specimens, into the wear stages (hereafter WS) of Dawson and Robson Brown (2013).

Fig. 1. Crown height measurements (for descriptions see text).

For each individual, the value of CI, PD and WS was taken as that from the left tooth of a pair, unless the left was missing in which case the value for the right side was substituted. To assess intra-observer error of CI, PD and WS, 20 mandibles were re-recorded. These mandibles were chosen to cover the full age range but were otherwise selected at random. Each specimen was re-photographed, with re-positioning, and re-measured for CI and PD. WS was re-scored from the specimen. Repeatability of CI and PD was assessed using the method error statistic (Dahlberg, 1940; Knapp, 1992); repeatability of WS using linearly weighted kappa (Cohen, 1968; Viera and Garrett, 2005).

Polynomial regression equations express the relationship between two ratio scale or interval scale variables in the form $y = a + b_1x + b_2x^2 \ldots b_nx^n$. Polynomial regression is a useful technique for investigating whether a relationship is linear or non-linear, and if the latter, characterising the form of the relationship (Cohen et al., 2003: 193–221). This approach was used in order to investigate relationships of CI and PD (the dependent variables) with dental age. It was also used as a heuristic device to study the relationship between CI and PD, with CI arbitrarily considered the dependent variable. Polynomial regressions for each dependent variable were fitted using a forward selection procedure (Zar, 1999: 452–459) in which x terms of successively higher power were added to the equation. The criteria of entry of successive x terms was that they significantly improved the prediction of y values at $p < 0.05$ according to the F statistic. For WS, rank correlation coefficients were used to investigate whether there was a valid relationship between WS and CI or dental age.

3. Results

The dental age distribution of the study sample is shown in Fig. 2. All but two of the study group had dental ages of 18 months or over, so the sample is essentially of fully weaned individuals (Richards et al., 2002). The repeatability study suggests that about 4–7% of the variance in CI is made up of measurement error; the corresponding figure for PD is 1–2% (Table 1). The kappa values for rescoring of WS were 0.83 for dm1 and 0.84 for dm2. These correspond to ‘almost perfect agreement’ on the scale of Landis and Koch (1977).

The regression procedure indicated that, for both dm1 and dm2, the relationship between CI and dental age is negative, is statistically significant ($p < 0.05$) and is adequately described by a linear regression equation (Table 2, Fig. 3). In general, in plots of crown height against age, if inter-individual variations in the rates of wear are great, then we might expect the scatter of points about the regression line to increase with age. However, the standardised residual plots (Figs. 4 and 5) show little evidence for this. This implies that variation in CI in unworn teeth or differences in the ages at which individuals began eating solid foods may be dominant factors in determining the spread of points about the

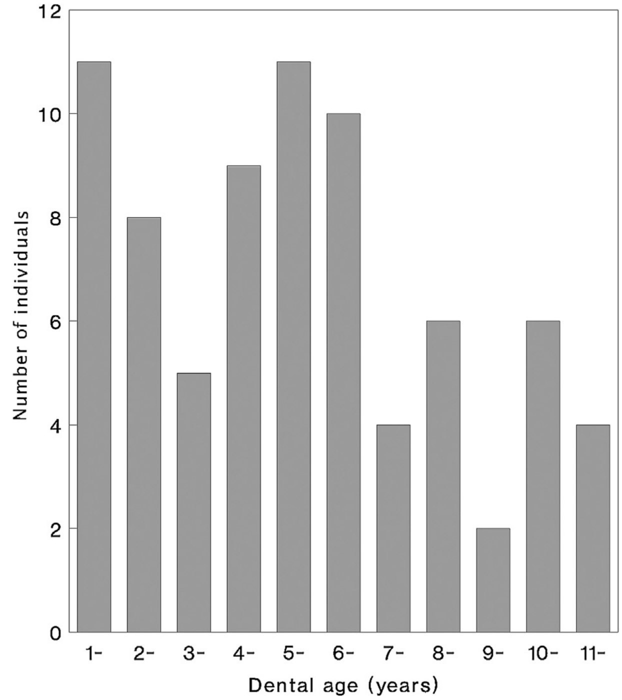

Fig. 2. The dental age distribution of the study sample ($N = 76$). 1- denotes 1–1.99yrs etc.

regression line. The slope of the regression line for dm2 is greater than that for dm1; analysis of covariance (ANCOVA) indicates that the difference is statistically significant ($t = 2.55$, $p = 0.01$). It might be suggested that the slight difference in the way in which MCH was taken on dm1 and dm2 might be at play here. To test this, CI was recalculated as 100 × DCH/MDL (DCH was defined is an analogous manner on dm1 and dm2); the difference in slopes persists (ANCOVA: $t = 2.17$, $p = 0.03$) indicating that it is not an artifact of the discrepancy in the way in which MCH was measured on the two molars. In dm1, mean MDL is 91% of that in dm2 (based on comparison of left dm1 and dm2 in 60 individuals). Because the divisor of CI is greater in dm2 than dm1, the difference in slopes would be even more marked had raw crown heights been measured instead of CI. These observations suggest that wear is faster in dm2 than dm1, to the extent to which inferences can be made from cross-sectional data sets. The correlation coefficient between CI and dental age was greater for dm2 than for dm1; the difference was statistically significant ($Z = 2.17$, $p = 0.03$).

Turning to the results for PD, 20 of the 76 dm1s showed no dentine exposure; for dm2 the corresponding figures were 16 out of 74 (two unerupted dm2s could not be scored for PD because the margins of the occlusal surfaces were obscured on the photographs by the edges of the bony crypts). Mean dental age of individuals with no dentine exposed on the dm1 was 3.4yrs, and for the dm2

Table 1
Method error for crown height index (CI) and percent dentine exposed (PD) ($N = 20$ repeats).

Variable	Tooth	S_m	S	S_m^2/S^2
CI	dm1	0.024	0.094	0.065
	dm2	0.021	0.101	0.043
PD	dm1	0.011	0.092	0.014
	dm2	0.013	0.126	0.011

S_m, standard deviation of the measurement (method error statistic); S, sample standard deviation.

Table 2
Regression equations for crown height index (CI) and percent dentine exposed (PD) upon dental age.

Variable	Tooth	N	Regression equation	r
CI	dm1	76	CI = 74.32–1.44 (age)	0.515
	dm2	72	CI = 75.16–2.44 (age)	0.733
PD	dm1	56	PD = −2.30 + 1.39 (age)	0.504
	dm2	58	PD = 5.25–2.92 (age) + 0.434 (age)^2	0.738

Data for PD only for those molars showing some dentine exposure. r, Pearson's correlation coefficient. All r values significantly different from zero at $p < 0.05$ by the F statistic. Four dm2s could not be measured for CI as they were not sufficiently erupted, hence $n = 72$.

2.8yrs, the range in each case being from 15 months to 8–9 years. Analysis of PD results was restricted to those teeth showing some dentine exposure. In contrast to the results for CI, both molars show a marked increase in spread of PD values with dental age (Figs. 6 and 7). For dm1, adding power terms of age did not improve the fit over the simple linear regression equation for PD upon age. For the dm2, the regression procedure identified a quadratic relationship (Table 2), with little variation in PD those under about 6 years but an increasingly rapid change at older ages (Fig. 7).

For the dm2 the regression procedure identified a quadratic relationship between CI and PD (CI = 65.45 − 1.30(PD) + 0.186(PD)^2). There is a distinct levelling off in CI at higher PDs (over about 25%), suggesting that once about one quarter of the occlusal surface is exposed dentine, minor decrements in crown height may be associated with large increments in exposed dentine (Fig. 8). For dm1, the relationship between CI and PD appears more linear (Fig. 9). This is confirmed by the regression results which show that adding power terms of PD failed to improve the fit over a linear equation (CI = 67.94 − 0.56(PD)). To some extent this may reflect the observation that fewer dm1s than dm2s show advanced occlusal wear – it is only in more heavily worn teeth that the levelling off in the relationship between CI and PD in the dm2 became apparent (Fig. 8).

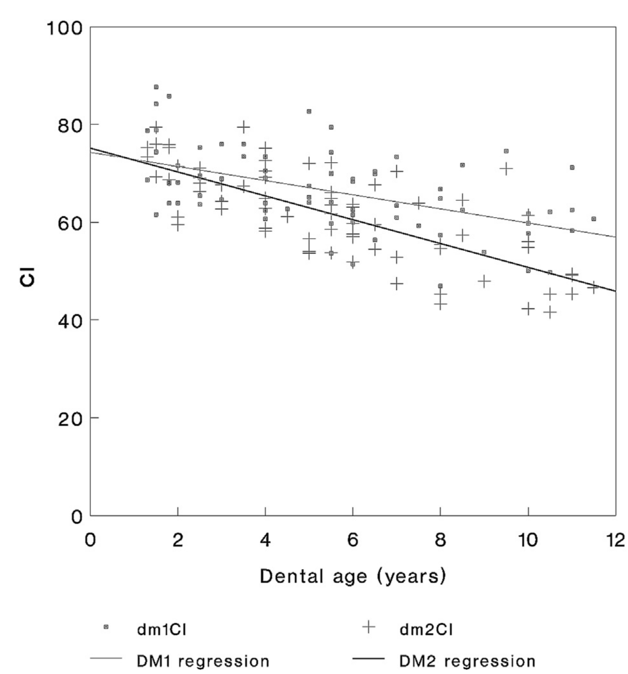

Fig. 3. Crown height index (CI) versus dental age for dm1 and dm2. The linear regression lines of CI upon dental age for each tooth are superimposed.

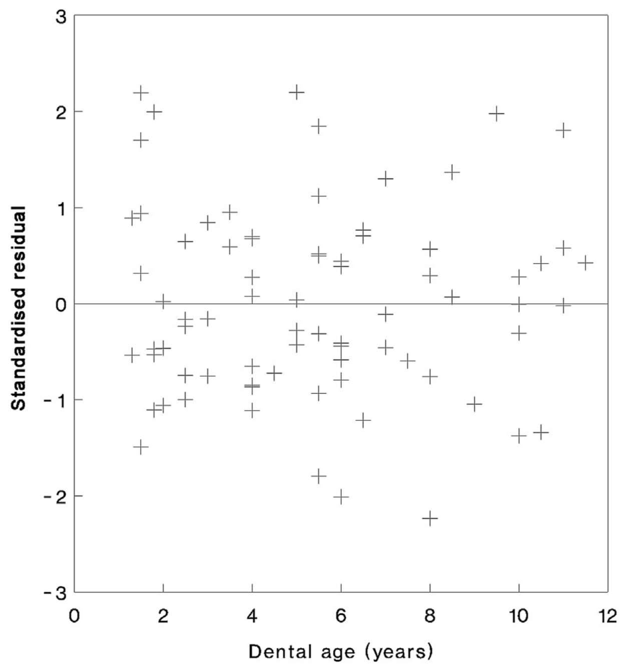

Fig. 4. Standardised residuals from the linear regression of crown height index (CI) upon dental age, versus dental age, for dm1.

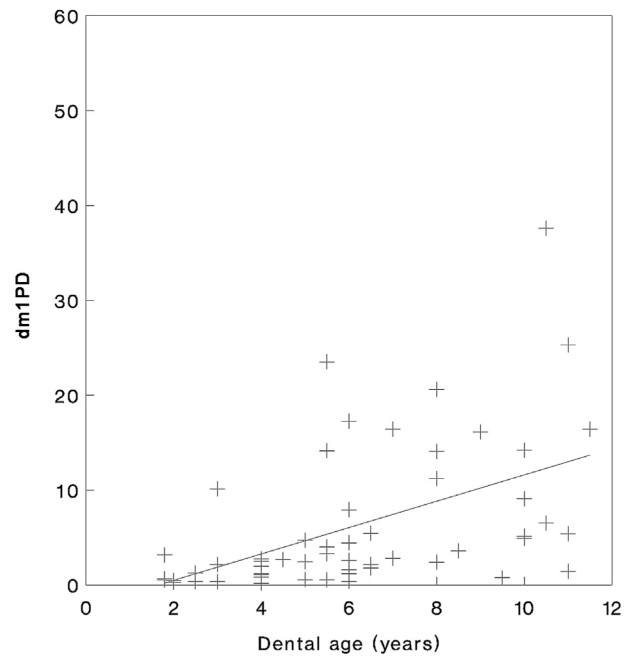

Fig. 6. Percent exposed dentine (PD) versus dental age for dm1. The linear regression line of PD upon dental age is superimposed.

Results for CI versus WS are shown in Table 3 and Figs. 10 and 11. WS versus dental age is plotted in Figs. 12 and 13. For CI and WS, Spearman's rank correlation coefficients are −0.54 and −0.60 for dm1 and dm2 respectively, both are significantly different from zero ($p < 0.001$). The difference between the two correlation coefficients is not significant ($Z = 0.51$). From about WS 5 (moderate dentine exposure) onward, the mean CI, expressed as a percentage of the mean CI in unworn teeth, is less in the dm2 than in the dm1 (Table 3). This suggests that a greater loss of CI is needed in order to reach the higher WS in dm2 than in dm1. Both dm1 and dm2 show positive rank correlation coefficients between dental age and WS (Spearman's $R = 0.64$ and 0.84 for dm1 and dm2 respectively, in each case $p < 0.001$). The difference between these rank correlation coefficients is statistically significant ($Z = 2.74$; $p = 0.007$), indicating a stronger relationship between WS and dental age in the dm2.

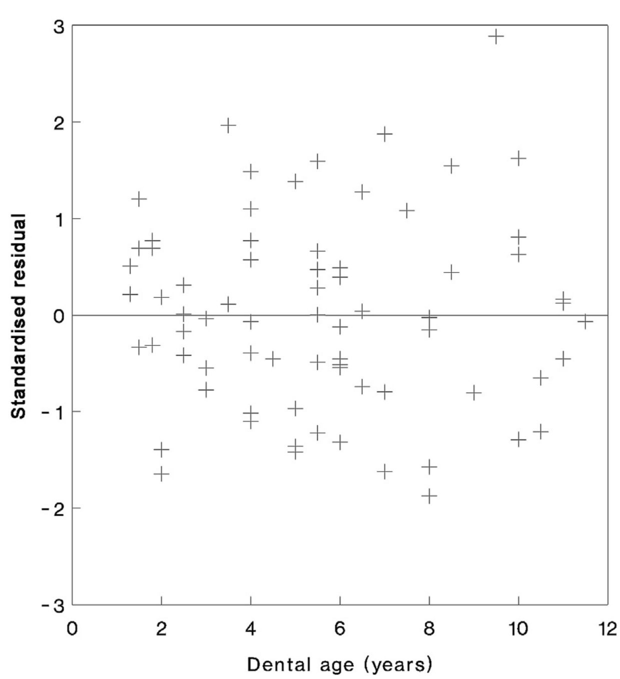

Fig. 5. Standardised residuals from the linear regression of crown height index (CI) upon dental age, versus dental age, for dm2.

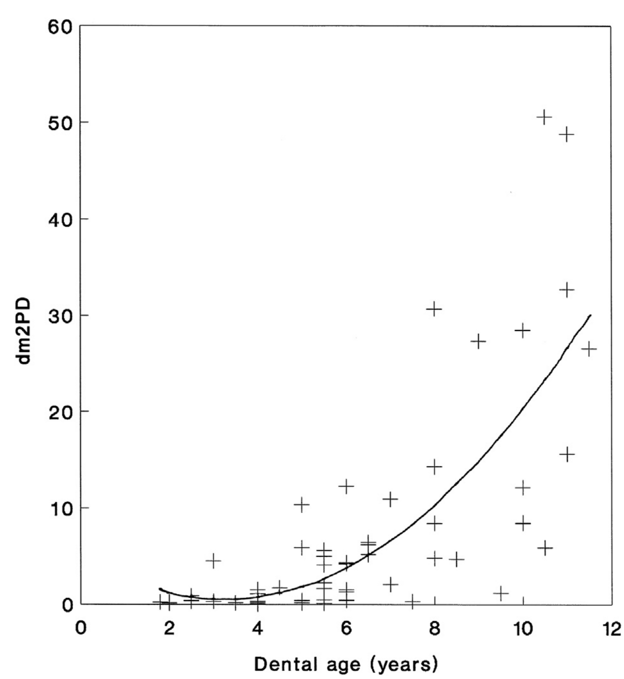

Fig. 7. Percent exposed dentine (PD) versus dental age for dm2. The quadratic regression line of PD upon dental age is superimposed.

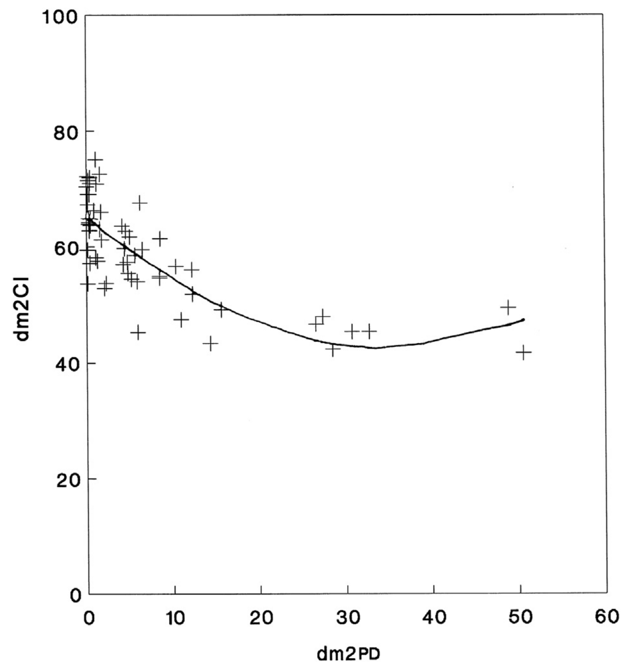

Fig. 8. Crown height index (CI) versus percent exposed dentine (PD) for dm2. The quadratic regression line of CI upon PD is superimposed.

4. Discussion

Various factors might potentially alter the rate of wear on the deciduous molars during the time they are in occlusion. Bite-force that can be exerted approximately doubles during that period (Kamegai et al., 2005). The eruption of the first permanent molar, at approximately six years of age, increases the total occlusal area available in the dentition for crushing and grinding. However these factors produced no effect on wear rates that was discernable in this (cross-sectional) data set: the relationship between CI and dental age was approximately linear throughout the life-time of the deciduous molars. This parallels results on the first permanent molar in another early British population: in juveniles with dental ages 6–18yrs from 3rd–4th century AD Poundbury the relationship between crown height and dental age was essentially linear, despite an increase in bite force across that age range and the eruption of the second permanent molar at about 12 years (Mays et al., 1995).

Table 3
Summary statistics for crown height index (CI) split by WS.

WS	dm1			dm2		
	N	Mean (sd)	% wrt unworn molar	N	Mean (sd)	% wrt unworn molar
0	3	76.0 (13.2)	(100)	6	74.8 (3.3)	(100)
1	4	75.9 (6.9)	99.9	3	65.1 (5.6)	87.0
2	7	70.7 (5.8)	93.0	5	69.7 (7.7)	93.2
3	5	69.2 (7.6)	91.1	11	66.2 (5.6)	88.5
4	21	67.4 (7.0)	88.7	9	67.3 (6.9)	90.0
5	7	63.8 (4.8)	83.9	15	58.6 (6.1)	78.3
6	9	68.5 (7.9)	90.1	13	57.6 (6.6)	77.0
7	12	63.6 (4.8)	83.7	1	51.9 (−)	69.4
8	8	55.3 (6.2)	72.8	9	47.1 (4.3)	63.0

WS 9 and 10 were not observed in the study group. % wrt unworn molar, mean CI for wear stage expressed as a percentage with respect to the mean value for unworn teeth (i.e. WS 0).

Teeth are anisotropic in their mechanical properties. Enamel is harder than dentine (Low et al., 2008), and enamel is harder at the surface, with hardness decreasing toward the junction with dentine (Cuy et al., 2002). Hardness of dentine decreases in proximity to the pulp cavity (Ranjitkar et al., 2008). These factors might be expected to result in alterations to the rate of dental wear as the crown is progressively worn down. In particular, the hardness difference between dentine and enamel has led to the assumption that teeth will wear faster once there is significant dentine exposure on the occlusal surface (Molnar, 1971; Miles, 1978; Lambrechts et al., 1989;

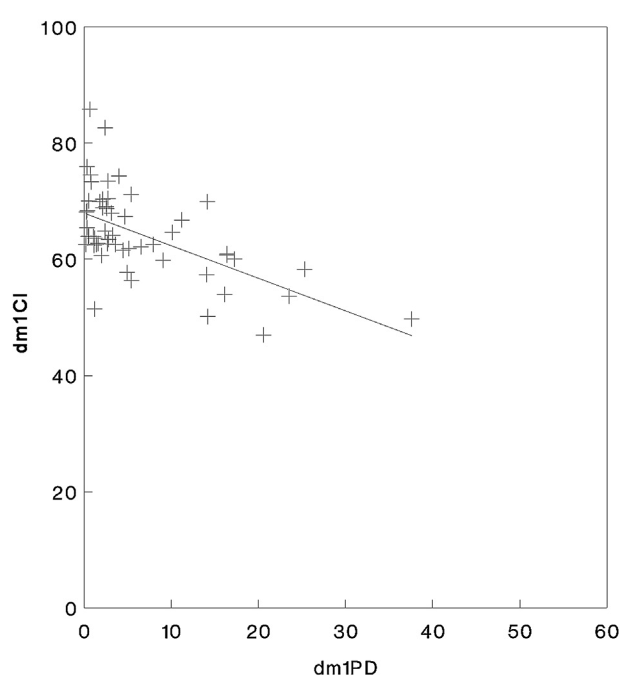

Fig. 9. Crown height index (CI) versus percent exposed dentine (PD) for dm1. The linear regression line of CI upon PD is superimposed.

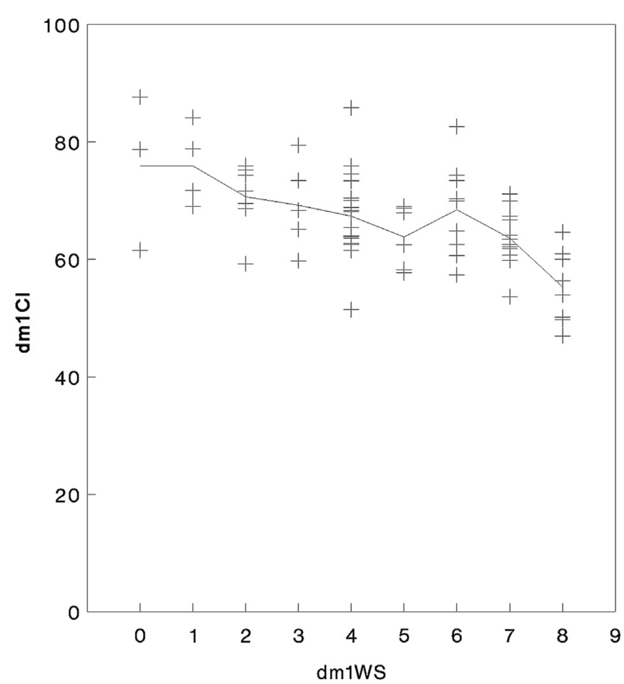

Fig. 10. Crown height index (CI) versus wear stage (WS) for dm1. The trend line connects mean CI for successive WS.

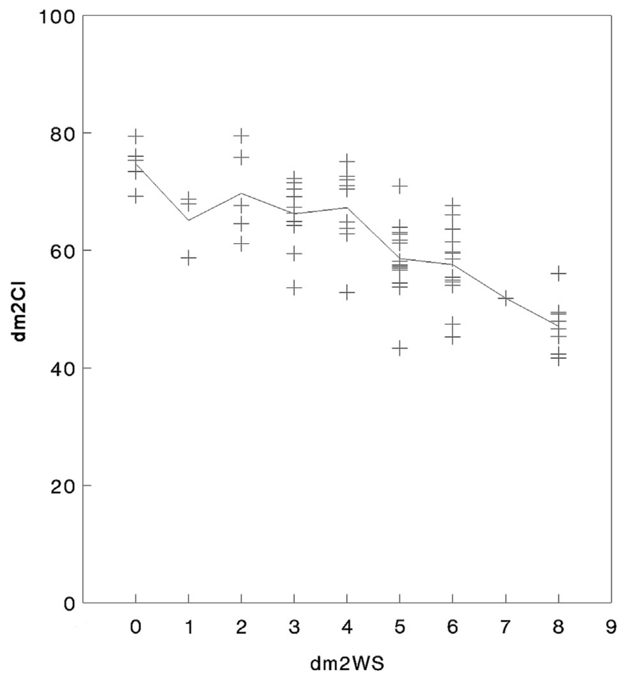

Fig. 11. Crown height index (CI) versus wear stage (WS) for dm2. The trend line connects mean CI for successive WS.

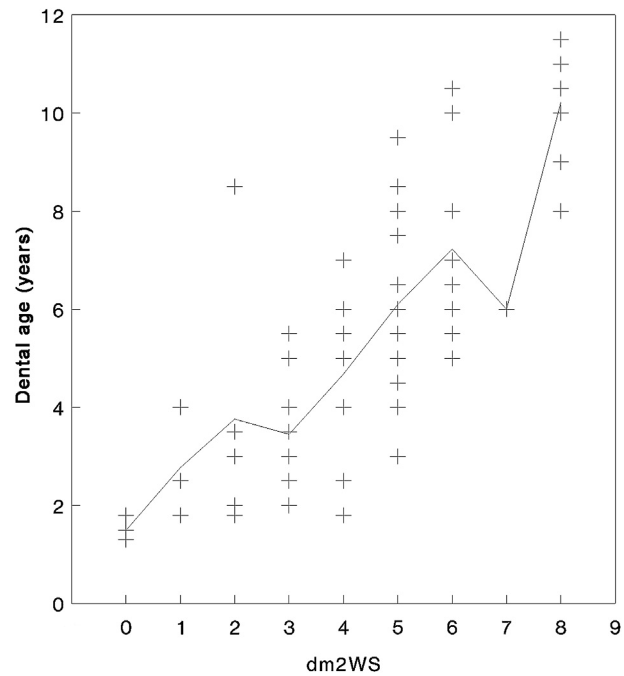

Fig. 13. Dental age versus wear stage (WS) for dm2. The trend line connects mean dental age for successive WS.

Bell et al., 1998). The present study provides no evidence for this effect in dm1 or dm2. It might be suggested that this is due to the fairly modest amount of dentine exposed on the deciduous molars before they are shed (Figs. 6 and 7), and the fact that enamel on deciduous teeth is softer than that on permanent teeth (Low et al., 2008) so the contrast in hardness between enamel and dentine is less. However, a linear relationship has also been observed between

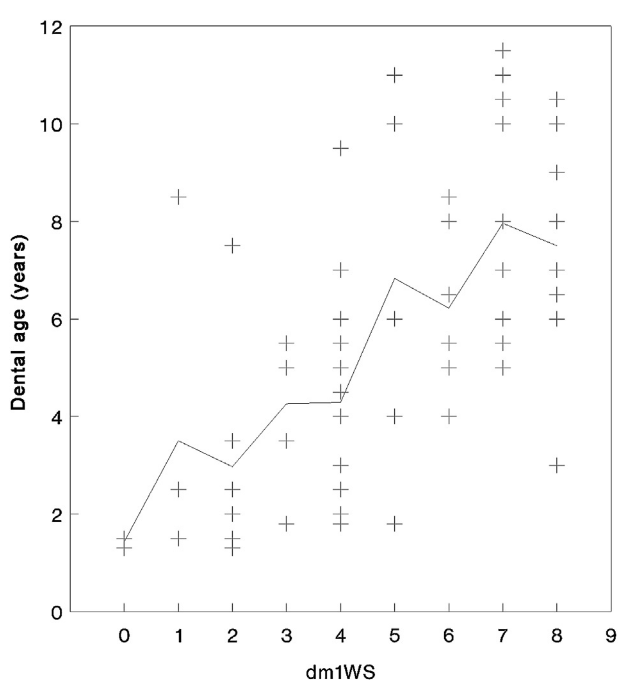

Fig. 12. Dental age versus wear stage (WS) for dm1. The trend line connects mean dental age for successive WS.

crown height and age in permanent molars in adults (Mays, 2002; Benazzi et al., 2008) in populations where there is rather greater dentine exposure during the lifetime of the permanent molars than is the case here with the deciduous molars. It may be that the assumption that dentine inevitably wears more rapidly than enamel is misplaced. In vitro studies (Burak et al., 1999; Richards et al., 2010) show that, at low occlusal loads, dentine does wear faster than enamel, but at higher loads the brittle nature of enamel means that wear resulting from microfracturing of the occlusal surface increases, whereas the collagen matrix of dentine makes it less vulnerable to microfractures under high loading (Lewis and Dwyer-Joyce, 2005). Wear rates of dentine may exceed those of enamel only under loadings less than about 120 N (Richards et al., 2010). Bite forces reported in the orthodontic literature differ substantially between studies using different methodologies, but adults consuming modern Western diets may regularly exceed this level of occlusal loading during mastication (Mornebürg and Pröschel, 2002). It appears to lie toward the upper limit of bite forces that have been recorded in children with deciduous dentition (Braun et al., 1996; Rentes et al., 2002; Kamegai et al., 2005; Gavião et al., 2007; Mountain et al., 2010), but it seems plausible that, in ancient populations with diets requiring vigourous mastication, it may have been regularly attained, even in children. High occlusal forces may be a factor in the lack of evidence for alteration in wear rates with exposure of dentine in deciduous molars in the current study group, and in similar observations on the permanent molars of other palaeopopulations.

Despite the dm2 having a larger occlusal area than the dm1, at Wharram Percy, the CI data indicated that the dm2 wore at a faster rate, to the extent to which inferences can be made from a cross-sectional data set. Mahoney (2010) suggests that the dm2 may perform greater crushing and grinding (and less shearing) of food than the dm1 due to lesser lateral excursion of the mandible closer to the temporo-mandibular joint. If correct, this may be a factor here. Another possibility is that mastication simply occurred preferentially on the dm2.

In the study group, 26% of dm1s and 22% of dm2s show no dentine exposure, so the PD method could not be used to assess wear. Given that the dental wear rates at Wharram Percy typify those in early British populations, this is a serious limitation of the method for British material, but it would be expected to be less of a problem for populations with more rapid wear – eg hunter-gatherers (Larsen, 1997: 250–251) or groups from desert environments where foods may be contaminated with large amounts of mineral grit (Leek, 1984). Unlike CI, there was a marked heteroscedasticity in the plot of PD versus dental age, with an increasing spread of PD with age. In the dm2, the age relationship was optimally described by a quadratic rather than linear equation. These findings may be more general: Richards and Miller (1991) found similar heteroscedasticity in their plots of proportion of the occlusal surface of permanent first molars made up of exposed dentine in adults of known age, and the relationship was also non-linear resembling that seen in dm2 in the current work.

The relationship between PD and CI was also of non-linear form in the dm2 so that, in teeth showing heavier wear, PD varied widely across individuals with similar CI. This suggests that, in more worn dm2s, small differences in CI may be associated with large differences in PD. This may be consistent with the observation, made earlier, that in the study population, patches of exposed dentine were often surrounded by areas of rather thinned enamel – in such cases a minor decrements of crown height might be associated with large increments in exposed dentine. This non-linear pattern was not evident in the dm1, but the slower wear on that tooth meant that advanced wear was rarely seen; in higher dental wear populations the pattern seen here in dm2 might potentially be reproduced in dm1.

For both dm1 and dm2 there was a positive relationship between WS and dental age. As for CI, the relationship was stronger for dm2 than for dm1. From a dental age of 3–4 years the majority of dm1s show dentine exposure; for dm2s the corresponding figure is 5–6 years. Given the timing of eruption of these teeth, these figures correspond to about 1.5–3 years of wear on dm1 and 3–4.5 years of wear on dm2. That more years of wear are required to produce dentine exposure on the dm2, despite its more rapid loss of crown height, is presumably due to the thicker enamel characteristic of this tooth (Zilberman et al., 1992; Bayle et al., 2009; Mahoney, 2010). These figures compare with about 7–11 years of wear required to produce dentine exposure in the permanent M1 in this population (Mays et al., 2007). The less time required to expose dentine on the deciduous teeth, despite the lower bite forces in young children, presumably reflects their softer, thinner enamel (Low et al., 2008; Mahoney, 2010).

There was a significant, negative relationship between CI and WS confirming that increasing WS corresponds to progressive removal of crown height, but there is something of a plateau in the relationship at WS 5–7 (Figs. 10–11). These WS correspond to moderate – considerable dentine exposure (Dawson and Robson Brown, 2013) so, consistent with inferences made earlier, the pattern suggests that in more heavily worn teeth fairly minor decrements in CI may be accompanied by large differences in exposed dentine. The higher WS appear to correspond to a lesser CI, relative to that in unworn teeth, in dm2 than in dm1, suggesting that they correspond to removal of differing amounts of crown height in the two molars.

5. Conclusions

Crown height, as recorded here, the method of Clement and Freyne (2012) quantifying dentine exposure, and the Dawson and Robson Brown (2013) ordinal wear stages, each offer useful and repeatable means of recording wear on the deciduous molars.

At Wharram Percy, the relationships between PD and age and PD and CI were rather heteroscedastic with a wide scatter of PD at more advanced ages and more worn teeth (indicated by lower crown heights). This heteroscedasticity may be a result of the anatomical structure of the molar teeth and hence not be restricted to the current study group. This necessitates non-linear approaches or transformation of variables when controlling for age effects in dietary studies. Another drawback of the PD method is that a significant proportion of teeth are excluded from analysis because they do not show dentine exposure.

The WS method provides a more rapid means of recording dental wear than either CI or PD. However, the substitution of ratio-scale data with ordinal-scale data inevitably results in loss of information. Differences in tooth structure mean that wear stages correspond to different amounts of crown height removed (inferred from the CI data) on dm1 and dm2. Although there was a strong, negative rank correlation between CI and WS in both deciduous molars, different WS appeared not to correspond to similar increments of crown height.

CI showed a significant, negative, linear relationship with dental age in both dm1 and dm2. The current study adds to earlier work on permanent teeth in indicating a linear relationship between molar crown height and age in children in populations showing significant dental wear (Molnar et al., 1983; Mays et al., 1995), despite (amongst other things) the marked changes in bite force that occur during ontogeny. The regression residuals were homoscedastic suggesting that inter-individual differences in rates of wear were fairly small. Wear appeared more rapid on dm2 than on dm1. Reasons for this are unclear, but presumably relate to differences in functional loading between dm1 and dm2. A mathematical description of the relationship between molar wear, measured as a ratio-scale variable, and dental age is potentially useful in childhood dietary studies because it establishes a datum for the population under study from which departure, associated with disease, nutritional or social variables, can be evaluated statistically. When, as in the current case, the relationship is of approximately linear form, intra- and inter-population analyses of this type can be readily conducted using simple statistical methods, such as multiple regression or analysis of covariance. Further work is needed to investigate the extent to which the current results apply to other palaeopopulations (for example, with different diets), but they do suggest the potential value of deciduous molar crown height for dental wear studies of childhood diets.

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